







Detrital zircon records of the Paleo-Mesoproterozoic rift-sag Tamanduá Group in its type-section, Northern Quadrilátero Ferrífero, Minas Gerais, Brazil

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Abstract

The Quadrilátero Ferrífero metallogenetic province is located in the southernmost portion of the São Francisco craton, SE Brazil. The Tamanduá and Cambotas ridges stand out topographically in the northeastern portion of Quadrilátero Ferrífero and show NE-SW and N-S directions, respectively. Those ridges involve metasedimentary rocks of the Tamanduá Group bounded by a fault system. Due to stratigraphic and structural complexities, there is little consensus about the maximum sedimentation age and the stratigraphic position in which Tamanduá Group sediments were deposited. In this work, we took advantage of the excellent exposures in the Tamanduá and Cambotas ridges to present detailed stratigraphic observations combined with U-Pb zircon geochronological data from samples of different stratigraphic levels of Tamanduá Group. Furthermore, we provide U-Pb data from samples of the intrusive Pedra Formosa Suite that cut the whole Tamanduá sequence in the study area. Our observations showed that the Tamanduá Group represents a rift-sag basin-fill succession developed along the eastern border of the São Francisco paleoplate. The basal metaconglomerate and metasandstone package grades upward into marine metasandstone and phyllite. Detrital zircon obtained from the basal unit, Antônio dos Santos Formation, reveals maximum depositional ages between ca. 1981 and 1770 Ma. The upper succession, Cambotas Formation, shows a maximum depositional age from 1769 to 1740 Ma. The Pedra Formosa Suite shows zircons that crystallized at ca. 1740 Ma. The stratigraphic framework and the Orosirian-Statherian ages suggest a correlation with the first rifting event within the São Francisco paleoplate, the precursor of Paleo- to Mesoproterozoic Espinhaço basin.

KEYWORDS: Tamanduá Group; Espinhaço System; detrital zircons; São Francisco Craton; rift-sag sedimentation.

INTRODUCTION

In Proterozoic times, several sedimentary basins are registered in the interior and the boundaries of the Neoproterozoic São Francisco craton (SFC), southeastern Brazil (e.g., Alkmim and Martins-Neto 2012, Guadagnin and Chemale Jr. 2015). The intracratonic basins (Fig. 1) comprise several sedimentary sequences separated by unconformities as the main result of continuous and significant changing patterns of intraplate tectonic regimes (Alkmim and Martins-Neto 2012). Thus, when these unconformities are, to varying degrees, obliterated by tectonic inversion and metamorphism developed by the Orosirian and the late Neoproterozoic orogenies, the distinction between these basin cycles is compromised.

The Tamanduá and Cambotas ridges (Fig. 2) materialize the physical connection between the Gandarela syncline, a sub-regional NE-SW structure related to the Archean-Paleoproterozoic Quadrilátero Ferrífero metallogenetic province (QF, Iron Quadrangle), and the N-S Paleo-Mesoproterozoic Southern Espinhaço ridge. The Tamanduá and Cambotas ridges (Fig. 2) are the locus typicus of the metasedimentary Tamanduá Group described by Simmons and Maxwell (1961), considered as the fundamental unit in the northern QF to understand the temporal distribution of QF and Southern Espinhaço units, as pioneering observed by Harder and Chamberlin (1915) and Guimarães (1931), and later reinforced by Simmons and Maxwell (1961), Hirson (1967), Simmons (1968), Moore (1969), and Dorr II (1969). The temporal and stratigraphic positioning of the Tamanduá Group is speculative due to the absence of non-tectonic contacts between the metasedimentary sequences in the Gandarela, Tamanduá, and Cambotas ridges. Four hypotheses constitute the most disseminated stratigraphic proposals to the Tamanduá Group (Tab. 1). The early proposal points to the correlation of the Tamanduá Group with the QF units, i.e., Archean Rio das Velhas greenstone belt or Neoproterozoic Minas Supergroup. On the other hand, since the late 1970s, several authors have proposed the association of the Tamanduá Group with the Espinhaço Supergroup. Castro and Pedrosa (1982) suggested a hybrid hypothesis, correlating

Supplementary material

Supplementary data associated with this article can be found in the online version: [Supplementary data](#).

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Supergroup, highlighting its tectonics setting of the source area, depositional age, and evolution through time. The rocks of Caraça, Batatal, Ouro Branco, and Cambotas-Tamanduá ridges (Fig. 3) present lithostratigraphic similarities that led to the interpretation of a single unit (*i.e.*, Maxwell 1972, Dorr

II 1969, Angeli 2016, Romano *et al.* 2017). Nonetheless, geochronological studies and lithostratigraphic research indicate that the metasedimentary rocks belong to the Caraça, the Itacolomi or the Tamanduá Group (Almeida *et al.* 2005, Alkmim *et al.* 2014, Nunes 2016, Dutra 2017).

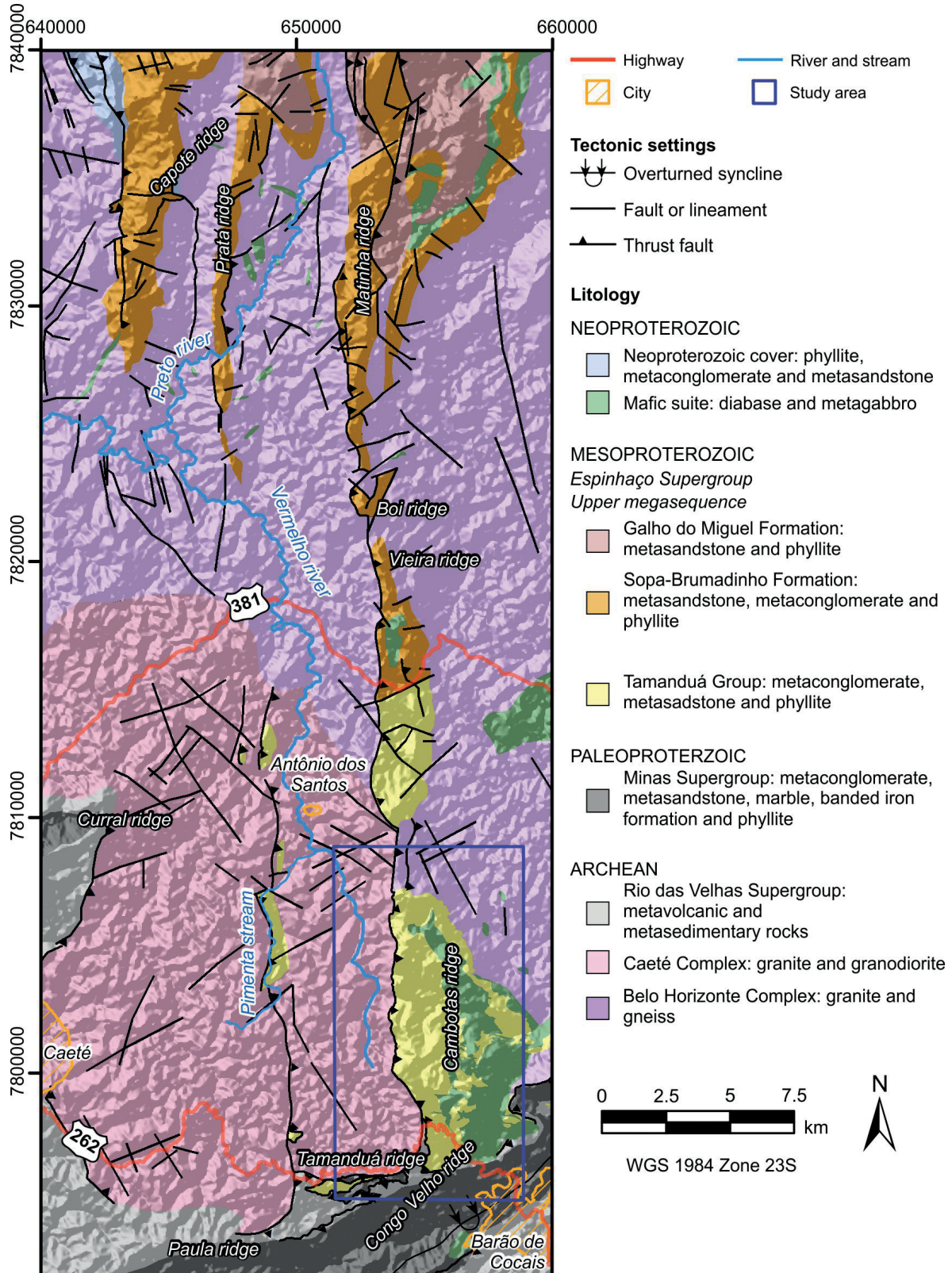


Figure 2. Composition of shaded relief and geological map of NE Quadrilátero Ferrífero and Southern Espinhaço ridge (based on Lobato *et al.* 2005, Saraiva 2012, Katakira 2013, Almeida-Filho *et al.* 2015, Gomes 2017). Hydrography data from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE 2017).

The previous U-Pb dating of detrital zircon ages of the Tamanduá Group provides inaccurate maximum depositional age (2258 ± 71 Ma, Machado *et al.* 1996), due to the low amount of grains analyzed, samples, and minimum concordance (70%). In order to evaluate sedimentary provenance, maximum/minimum depositional ages, and stratigraphic correlations, we combined stratigraphic observations and U-Pb analysis from nine samples of units of the Tamanduá Group and mafic suite in the Tamanduá and Cambotas ridges.

REGIONAL BACKGROUND

The SFC comprises Archaean nuclei, Archean-Proterozoic metavolcanic-sedimentary sequences, and Paleoproterozoic arc-related granitoids that host several sedimentary basins from the Proterozoic to Phanerozoic and are surrounded by Neoproterozoic orogenic belts (Fig. 1) (Almeida 1977, Alkmim and Martins-Neto 2012).

The Archaean nuclei outcrop in the southern and north-eastern portion of the SFC and encompass a mosaic of individual blocks bounded by Paleoproterozoic orogenic domains (Teixeira *et al.* 2017).

The southern exposure is represented by QF mining district and adjacent metamorphic complexes and greenstone belts (Teixeira *et al.* 2017). In the QF, the Archean kernels are formed by domal igneous-metamorphic complexes encircled by the Rio das Velhas greenstone belt (*i.e.*, dome-and-keel province; Cutts *et al.* 2019) and partially covered by the Paleoproterozoic Minas basin (Fig. 3).

Granite-gneiss complexes are continental blocks and juvenile arcs whose agglutination dates back to Paleo- to Neoproterozoic tectonomagmatic events (Romano *et al.* 2012, Lana *et al.* 2013). The first stage of emplacement dates back to ca. 3200 Ma (Santa Bárbara event) with tonalite-trondhjemite-granodiorite that served as the main kernels for crustal growth in 2900 Ma (Lana *et al.* 2013). The second stage, Rio das Velhas I event at 2920–2850 Ma, can be correlated to the development of the continental lithosphere in the southern portion of the SFC. The Rio das Velhas II event (2780–2730 Ma) is accompanied by high-grade metamorphism (Farina *et al.* 2016) and deposition of volcanic and mafic-ultramafic associations (Nova Lima Group) to turbidite deposits (Maquiné Group) of the Rio das Velhas Supergroup (Lana *et al.* 2013, Moreira *et al.* 2016, Martínez Dopico *et al.* 2017). The stabilization of Southern

Table 1. The hypothesis for the stratigraphic position of the Tamanduá Group.

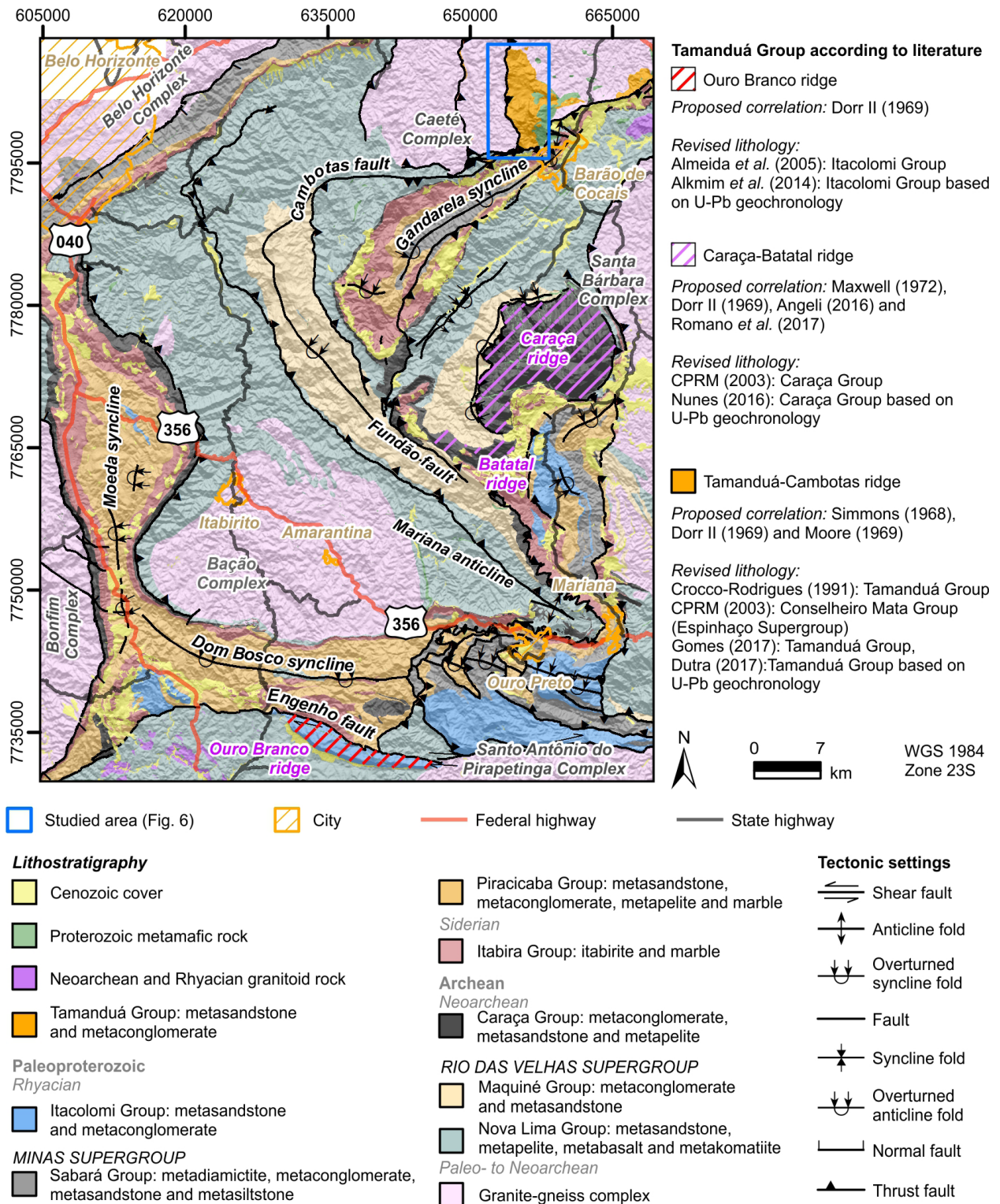
References	Rio das Velhas Supergroup	Minas Supergroup	Espinhaço Supergroup	Minas and Espinhaço supergroups
Simmons and Maxwell (1961)	■			
Hirson (1967)		■		
Simmons (1968)	■			
Dorr II (1969)		■		
Moore (1969)	■			
Herz (1970)		■		
Schöll (1972) ¹		■		
Maxwell (1972)	■		■	
Amaral <i>et al.</i> (1976)			■	
Schorscher and Guimarães (1976) ²			■	
Besang <i>et al.</i> (1977)			■	
Sperber (1977)			■	
Schorscher (1978, 1979a, 1979b, 1980)			■	
Herz (1978)	■			
Castro and Pedrosa (1982)				■
Ladeira (1982)			■	
Marshak and Alkmim (1989)			■	
Crocco-Rodrigues (1991)			■	
Freitas <i>et al.</i> (1991)			■	
Alkmim and Marshak (1998)		■		
CPRM (2003)			■	
Lobato <i>et al.</i> (2005)		■		
CPRM (2014)		■	■	

¹The rocks of the Cambotas ridge are part of the “Espinhaço zone” of the Minas Supergroup; ²they propose a chrono-correlation between the Minas and Espinhaço supergroups.

SFC is marked by potassium-rich granite in the Mamona event (2750–2700 and 2620–2580 Ma, Mamona I and Mamona II, respectively) (Farina *et al.* 2016, Martínez Dopico *et al.* 2017).

The Minas Supergroup unconformably overlies the Rio das Velhas greenstone belt and the granite-gneiss complexes (Fig. 3). The Minas basin records stages of a rift for marine sedimentation (Caraça and Itabira Group), passive margin (Piracicaba Group), and foreland basin (Sabará Group) (Dorr II 1969, Alkmim and Martins-Neto 2012). The Caraça Group comprises alluvial

metasandstone and metaconglomerate (Moeda Formation) that grade into marine deposits of the Batatal Formation. The Itabira Group comprises metamorphized Lake Superior-type banded iron formation (Cauê Formation) and carbonates (Gandarela Formation). The marine and deltaic sequence of Piracicaba Group overlie the Gandarela Formation through an erosional surface (Dorr II 1969). The basal unit, Cercadinho Formation, comprises Fe-rich metasandstone, phyllite and metaconglomerate. The Fecho do Funil and Taboões formations are made up



Source: generated from the Lobato *et al.*'s (2005) regional mapping shapefiles.

Figure 3. Geological map of the central portion of Quadrilátero Ferrífero and the occurrence of Tamanduá Group based on literature.

of phyllite, dolomitic marble and orthometasandstone. The top unit, Barreiro Formation comprises metasandstone and graphitic phyllite. The Sabará Group, top unit of Minas Supergroup, is separated from the previous sequence by regional unconformities. This group is made up of metadiamicite, metaconglomerate, metasandstone and metasilstone (Dorr II 1969, Reis *et al.* 2002). The Itacolomi Group is restricted in the southeast QF (Fig. 3). It comprises an alluvial sequence with marine transitions (Alkmim 1987) and lies the Minas Supergroup unconformably.

Mafic suites are very common in the QF, especially in the Caraça and Cambotas ridges (Fig. 3). Dykes show different trends and ages. Silva *et al.* (1995) reported a baddeleyite U-Pb upper intercept age of 1714 ± 5 Ma for Ibirité gabbro, one of the mafic dike swarms in the QF that cuts the Minas Supergroup. Additionally, Cederberg *et al.* (2016) recognized three NW-SE trending dike generations that intrude the granitoid complexes and Minas Supergroup in the western QF, dated at 1798–1793, 1717–1703, and 706 ± 36 Ma.

The SFC Paleo- to Mesoproterozoic cover is related to the Espinhaço system and exposed by several inner intracratonic basins and in their borders (Fig. 1). Those units present lithological and stratigraphic arrangement similarities (Brito Neves *et al.* 1995, Guadagnin and Chemale Jr. 2015). In general, those basins encompass continental sediments in a rift-sag environment, in a polycyclic and poly-historic evolution, associated with mafic and/or felsic alkaline magmatism between 1.8 and 1.68 Ga (Dussin and Dussin 1995, Danderfer *et al.* 2009, Danderfer Filho *et al.* 2015, Guadagnin and Chemale Jr. 2015). The opening of the Espinhaço basin is related to the crustal stretching in the aftermath of Minas accretionary orogeny (Machado and Abreu-Bentivi 1989). The crustal stretching may be the result of far-field stress (Danderfer Filho *et al.* 2015) or mantle plumes (Rosière *et al.* 2019). The Espinhaço basin fill-succession comprises three tectonostratigraphic megasequences, Lower Espinhaço (1.80–1.68 Ga), Middle Espinhaço (1.60–1.38 Ga), and Upper Espinhaço (1.2–0.9 Ga), which represent stages of the rift to sag basin (Chemale Jr. *et al.* 2012). The minimum age of Espinhaço basin is defined from the mafic intrusive dykes swarms dated 964–957 Ma (de Castro *et al.* 2019, Souza *et al.* 2019).

The structural framework of the northeast portion of the QF is the result of at least two deformational events, the first in the Rhyacian-Orosirian period (Minas accretionary orogeny) and the second in the Late Neoproterozoic (Alkmim and Marshak 1998, Endo and Machado 2002). Several structures are coeval with Minas accretionary orogeny that generated regional folds, such as Gandarela syncline, overprinted by Neoproterozoic fault systems, *i.e.*, Cambotas-Fundão fault system (Alkmim and Marshak 1998) and Córrego do Garimpo thrust belt (Crocco-Rodrigues *et al.* 1989).

Lithostratigraphy of Tamanduá and Cambotas ridges

The Tamanduá and Cambotas ridges are surrounded by Archean granitoid rocks and the Gandarela syncline (Figs. 2 and 3). The Archean complexes are represented by the

gneiss, migmatite, and granitoid (Brandalise and Heineck 1999) of the Caeté and Belo Horizonte complexes. Meanwhile, the Gandarela syncline gathers the rocks of the Nova Lima Group, Minas Supergroup, and Tamanduá Group in a NW-tectonic vergence, ENE-WSW axial trace, and inverted south limb.

The Nova Lima Group encompasses phyllite, chlorite, and sericite-quartz schist in the northern limb of the Gandarela syncline (Fig. 3). The Caraça Group occurs in discontinuous bodies near the Tamanduá ridge, which encompasses fine-grained sericite metasandstone (Moeda Formation) covered by sericite phyllite (Batatal Formation). The Itabira Group comprises itabirite (metamorphized banded iron formation, Cauê Formation) and dolomite (Gandarela Formation). The Tamanduá Group is represented by metasandstone and metaconglomerate in the Tamanduá ridge bounded by subsidiary thrust faults of the Cambotas fault.

The Fundão-Cambotas fault system presents the cartographic trace similar to that of the syncline and projects the Nova Lima Group on top of the Minas Supergroup (Fundão fault) and this unit on the Tamanduá Group (Simmons 1968, Moore 1969). This fault system and an erosive and angular surface separate the Itabira Group from the Nova Lima Group and the overlying Cercadinho Formation (Piracicaba Group). The fine- to medium-grained metasandstone interbedded with phyllite of Cercadinho Formation is the only unit of Piracicaba Group that outcrops in the NE QF. The Sabará Group is made up of phyllite and, locally, fine-grained metasandstone (Simmons 1968, Moore 1969, Alkmim and Marshak 1998, Dutra 2017, Dutra *et al.* 2019).

The Córrego do Garimpo thrust belt is interpreted as imbricated tectonic fans and encompasses the Córrego do Garimpo (the west limb of Cambotas ridge) and Montalvão faults (inner Caeté complex). This thrust belt shows an N-S direction and W-vergence (Crocco-Rodrigues 1991).

Stratigraphy of Tamanduá Group in its type-section

The lithostratigraphic description of the Tamanduá Group in its type-section was based on 1:10,000 geological mapping made by Gomes (2017), comprising the “Cambotas Quartzite” of Upper Unit of Simmons and Maxwell (1961) and the reviews proposed by Simmons (1968), Moore (1969), and Crocco-Rodrigues (1991).

The Tamanduá Group encompasses polymictic metaconglomerate and metasandstone that grades upward and laterally into metasandstone interbedded with metarkose and, as upper rocks, phyllite and sericite metasandstone. This sequence is divided into Antônio dos Santos and Cambotas formations, where, from the base to the top, the first one comprises the Córrego do Garimpo and Serra do Garimpo members and the second one, Rio Vermelho, São Miguel, and Ribeirão Cocais members (Gomes 2017) (Fig. 4).

The Córrego do Garimpo member (Figs. 5A and B) is made up of matrix- and clast-supported metaconglomerate with pebbles of quartz, banded iron-formation, granite-gneiss and micaeous, pure and ferruginous metasandstones. The pebble diameter ranges from 1 to 30 cm. The pebble tends to well-rounded

forms, but the banded iron-formation one is oblate in the less deformed portion of this rock. The predominant pebbles comprise metasandstone and banded iron-formation embedded in a matrix of very fine- to very coarse-grained quartz grains with a high level of micas. Occurrences of medium- to coarse-grained sericite metasandstone with sub-rounded to sub-angular grains are subordinate within the metaconglomerate. The Serra do Garimpo member comprises fine- to medium-grained

metasandstone with high angle cross-stratification, sub-rounded and well-sorted quartz grain (Figs. 5C and 5D).

The Cambotas Formation encompasses metasandstone and constitutes the most significant portion of the Cambotas-Tamanduá ridge. The Rio Vermelho member comprises fine- to coarse-grained metasandstone with metarkose bed and tabular stratification (Fig. 5E). Lowlands, plains, and meadows characterize its geomorphological domain in the Cambotas ridge. The São Miguel

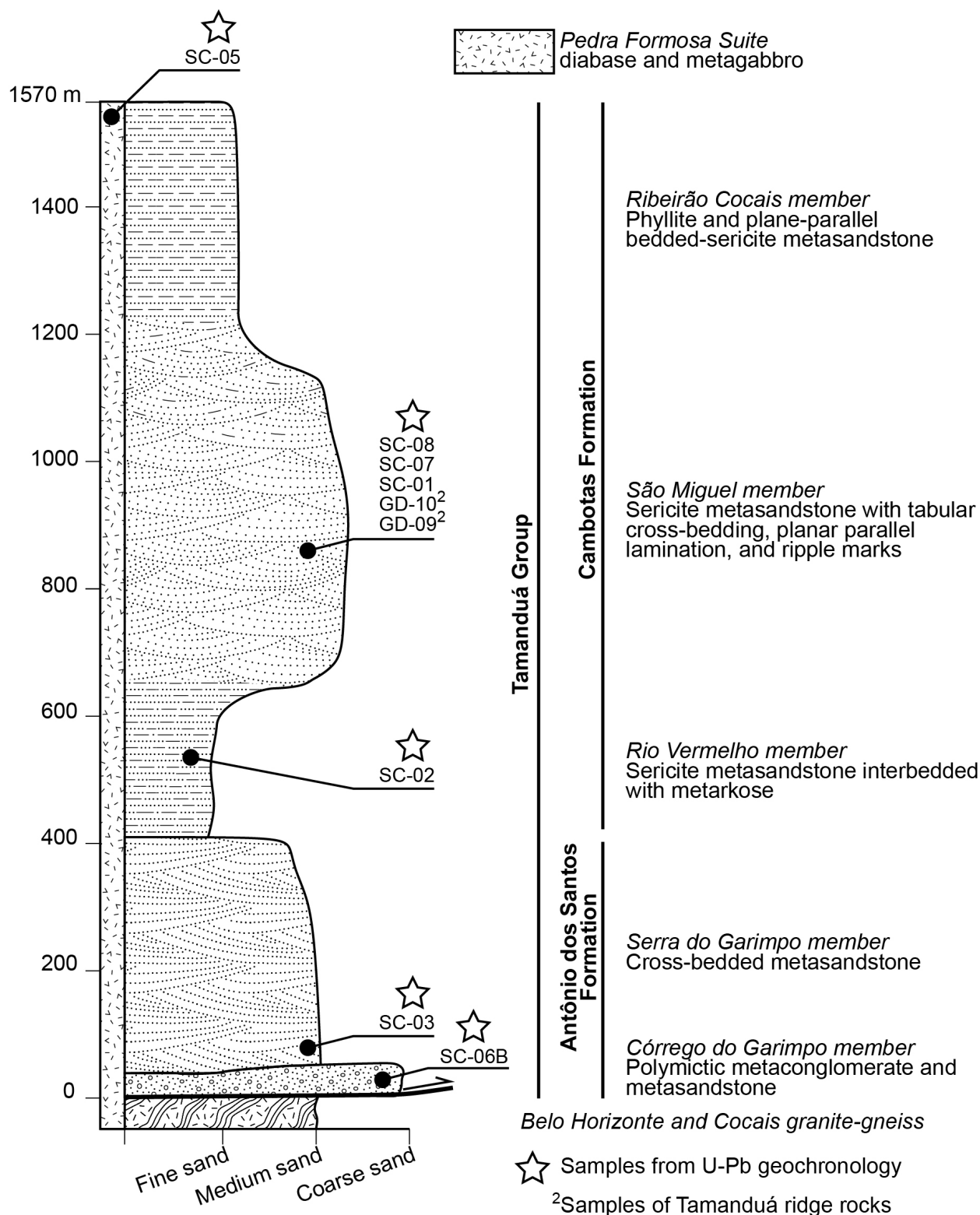


Figure 4. Stratigraphic column of Cambotas-Tamanduá range and the adjacent area proposed by Gomes (2017) (symboly by U.S. Geological Survey 2006).

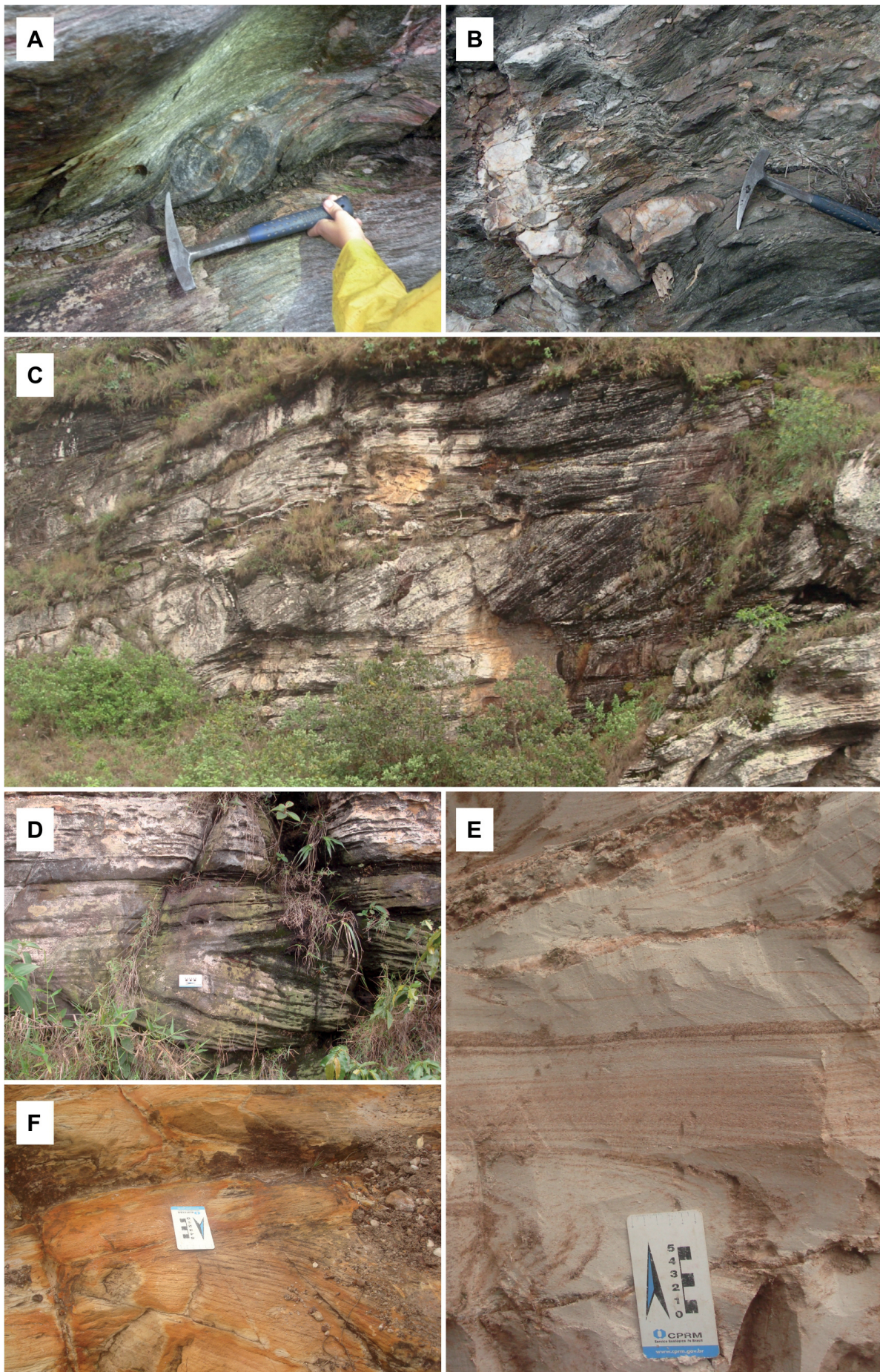


Figure 5. (A) and (B) Deformed matrix-supported metaconglomerate of Córrego do Garimpo member (Antônio dos Santos Formation) with well foliated matrix. (C) and (D) High-angle cross-stratified metasandstone of Serra do Garimpo member (Antônio dos Santos Formation). (E) Metasandstone with kaolin lenses of Rio Vermelho member (Cambotas Formation). (F) Cross-stratified metasandstone of São Miguel member (Cambotas Formation).

member (Fig. 5F) comprises fine- to coarse-grained metasandstone that ranges from orthometasandstone to mica metasandstone and large-scale cross-stratification, tabular cross-bedding, planar parallel lamination, and ripple marks. Generally, São Miguel metasandstone exhibits yellowish to brownish or pink color. The Ribeirão Cocais member is made up of very fine- to fine-grained metasandstone with planar parallel stratification and low-angle cross laminae, locally, occurs hummocky.

The contacts of the Tamanduá Group are marked by unconformity or faults (Simmons and Maxwell 1961, Simmons 1968, Moore 1969, Crocco-Rodrigues 1991) with the units of Rio das Velhas and Minas Supergroups and even with the granite-gneiss complexes (Figs. 2 and 3). The nature of contact between Antônio dos Santos and Cambotas formations is abrupt and tectonized (Gomes 2017).

Pedra Formosa Suite

The Pedra Formosa Suite comprises dykes, stocks, and sills that crosscut the Tamanduá Group. The diabase is black to bluish-gray and exhibits aphanitic texture. The metagabbro, a fine- to coarse-grained rock, is dark green (Crocco-Rodrigues 1991, Almeida-Filho *et al.* 2015, Gomes 2017). The intense weathering led to the development of thick cover of eutroferic dark-brownish and red latosol; thus, fresh outcrops are uncommon (Figure 6).

U-Pb GEOCHRONOLOGY

Samples and U-Pb dating

Samples were collected across the Cambotas ridge (Tab. 2, Fig. 7) from Antônio dos Santos Formation and Rio Vermelho

and São Miguel members of Cambotas Formation. The two samples of the Tamanduá ridge were analyzed by Dutra (2017).

About 15 kg of rocks for each sample (nine) were collected for U-Pb analyses of zircon grains and the entire procedure was conducted in the Departamento de Geologia of the Universidade Federal de Ouro Preto (DEGEO/UFOP). The samples were crushed and pulverized with a jaw crusher and grinder. Heavy minerals were concentrated by manual panning and, subsequently, by magnetic methods. Non-magmatic zircons were handpicked, and the grains were mounted in 25-mm-diameter epoxy mounts (SpeciFix). The preparation process was carried out in the Laboratory of Preparation of Geochronological Samples (LOPAG). After polishing, the zircon grains were imaged by Scanning Electron Microscope using a JEOL 6510 equipped with a Centaurus cathodoluminescence (CL) detector at the Microanalysis Laboratory (MICROLAB).

Zircon U-Pb isotopes were analyzed in a ThermoScientific Element 2 sector field (SF) ICP-MS coupled to a CETAC



Figure 6. Typical outcrop of Pedra Formosa Suite (courtesy of Mayko Neves).

Table 2. Summary of the geochronological samples of Tamanduá Group.

Samples	Coordinates (WGS 1984 23S)	Analyzed grains (concordant age zircon)	Unit	Description
SC-05	657619/7798343	59 (27)	Pedra Formosa Suite	Metagabbro
SC-08	654482/7801293	120 (102)		Very fine- to fine-grained sericite-metasandstone
SC-07	654040/7800963	118 (42)		Very fine- to fine-grained sericite-metasandstone with dispersed metasandstone and quartz clasts
SC-01	654237/7804593	119 (103)	São Miguel member (Cambotas Formation)	Moderated sorted fine- to medium-grained metasandstone with sub-angular to sub-rounded grains
GD-10 ¹	653032/7796006	60 (50)		Fine- to medium-grained metasandstone
GD-09 ¹	652277/7795656	89 (87)		
SC-02	654163/7805797	119 (53)	São Miguel member (Cambotas Formation)	Fine grained sericite-metasandstone
SC-03	654010/7807059	116 (95)	The base of Serra do Garimpo member (Antônio dos Santos Formation)	Well sorted fine- to medium-grained metasandstone with sub-rounded to rounded grains and cross-stratification
SC-06B	654219/7807213	119 (72)	The base of Córrego do Garimpo member (Antônio dos Santos Formation)	Matrix-supported metaconglomerate with metasandstone, quartz and iron formation banded clasts

¹Samples analyzed by Dutra (2017).

LSX-213 G2 + laser ablation system. Integration times were 15 ms for ^{206}Pb and ^{238}U , 40 ms for ^{207}Pb , and 10 ms for ^{208}Pb , $^{204}\text{Pb} + ^{204}\text{Hg}$, and ^{232}Th . The laser spot size was 20 μm and the repetition rate, 10 Hz. Helium was used as a carrier gas mixed with argon prior to introduction into the ICP-MS. Common Pb, instrumental mass discrimination and laser-induced elemental fractionation of Pb/U were corrected by normalizing the U/Pb and Pb/Pb ratios of the sample's zircons to zircon standards and Pb composition to the reference zircon GJ-1 (Jackson *et al.* 2004) of each analytical session (Stacey and Kramers 1975), using the Glitter software package (van Achterbergh *et al.* 2001). Multiple analyses of the Plešovice reference zircon

(Sláma *et al.* 2008) were performed during each session to test the validity of the method applied and the reproducibility of the age data obtained. The GJ-1 standard had weighted mean age of $605.3 \pm 0.9 \text{ Ma}$ (2σ , $n = 206$, MSWD = 1.8) whereas the Plešovice secondary standard had a weighted mean age of $335.8 \pm 0.7 \text{ Ma}$ (2σ , $n = 113$, MSWD = 1.7). The calculated ages agree, within uncertainty, with the accepted ID-TIMS ages reported for reference zircons by Jackson *et al.* (2004) and Sláma *et al.* (2008), respectively.

The signal data were initially reduced using the Glitter software package (van Achterbergh *et al.* 2001). An in-house Excel spreadsheet was used for taking all mass-bias and drifts

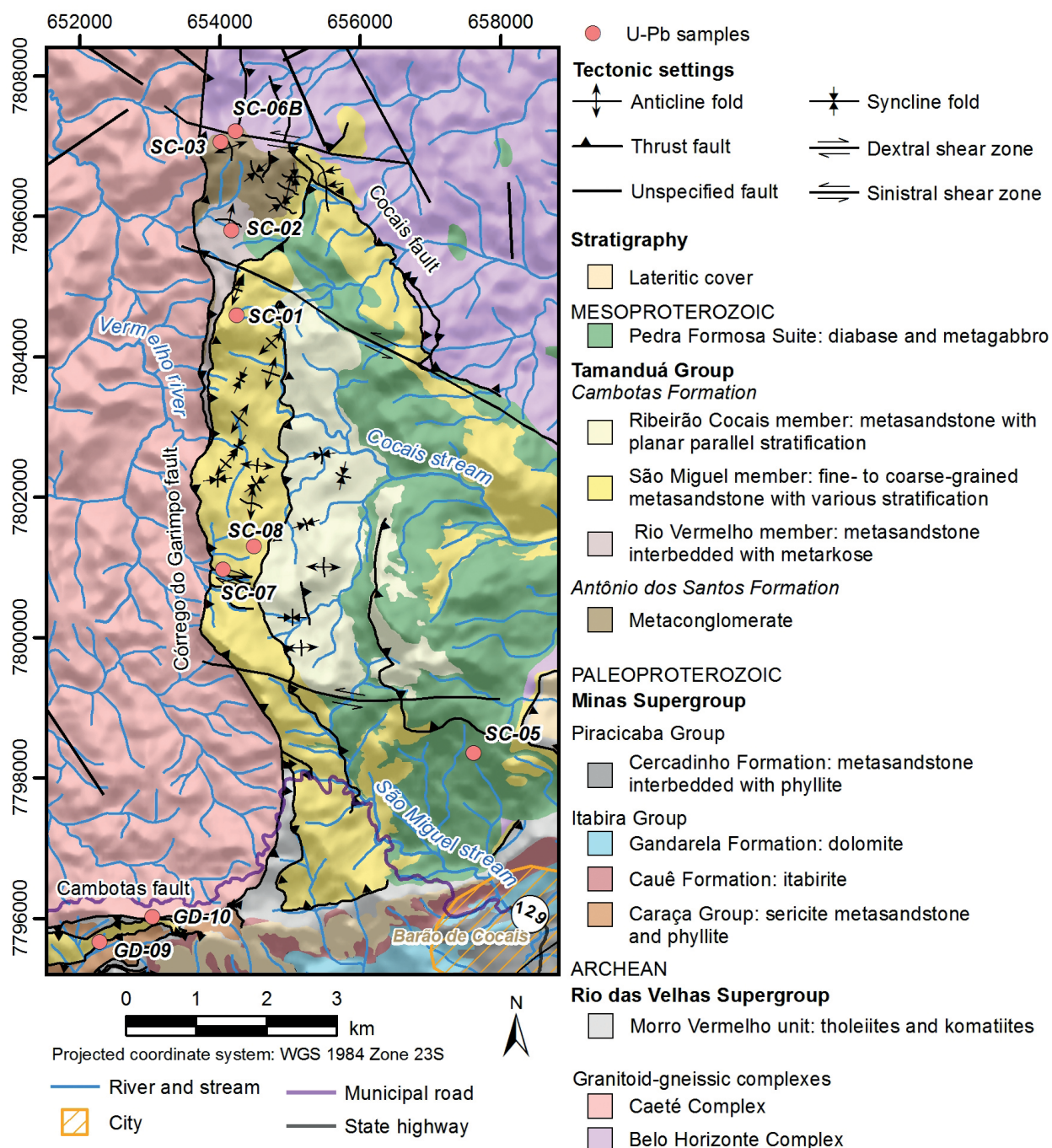


Figure 7. U-Pb geochronology samples of Tamanduá Group (based on Crocco-Rodrigues 1991, Brandalise and Heineck 1999, Saraiva 2012, Katurahira 2013, Almeida-Filho *et al.* 2015, Gomes 2017). Hydrography data from the Brazilian Institute of Geography and Statistics (IBGE 2017).

corrected counts exported from Glitter into account. The age distributions, concordia diagrams, and weighted mean ages were plotted and calculated with Isoplot 4.15 (Ludwig 2009).

The results of the LA-ICP-MS analyses for samples and reference zircons are reported in the Supplementary Data. The maximum discordance considered was 5%, and the diagrams are given by the $^{207}\text{Pb}/^{206}\text{Pb}$ ages and all errors are displayed as two standard deviations (2σ).

U-Pb Results

Zircon grains are mostly round and, in some cases, sub-hedral. The presence of fractures is frequent. The grains range from translucent to light brown and vary between 50 to 550 μm . CL images showed that most of the zircon grains have faint to complete absence zoning, with only a small number of grains exhibiting strong oscillatory zoning (Fig. 8).

The samples of Antônio dos Santos Formation have main peak age distribution (Fig. 9) between 2199–1962 Ma, followed by the Meso-Neoproterozoic population at 2590–2847 Ma. The sample SC-06B (Córrego do Garimpo member, Fig. 9H) shows the main population in the Rhyacian-Orosirian period (2248–1892 Ma, $n = 57$) followed by the Neoproterozoic one (2757–2590 Ma, $n = 11$). The youngest age is 1892 ± 20 Ma (99.9% conc.), and the older one (3452 ± 18 Ma, 97.9% conc.) predates the first Archean tectonomagmatic event, the Santa Bárbara event (ca. 3200 Ma). The sample SC-03 (Serra do Garimpo member, Fig. 9G) is like the previous one and shows its main peak in 2289–2032 Ma ($n = 76$). This sample has the youngest population ages of the Antônio dos Santos Formation, 1788–1724 Ma ($n = 4$).

The Cambotas Formation samples (SC-02 of Rio Vermelho member, and SC-01, SC-07, SC-08, GD-09, and GD-10 of São

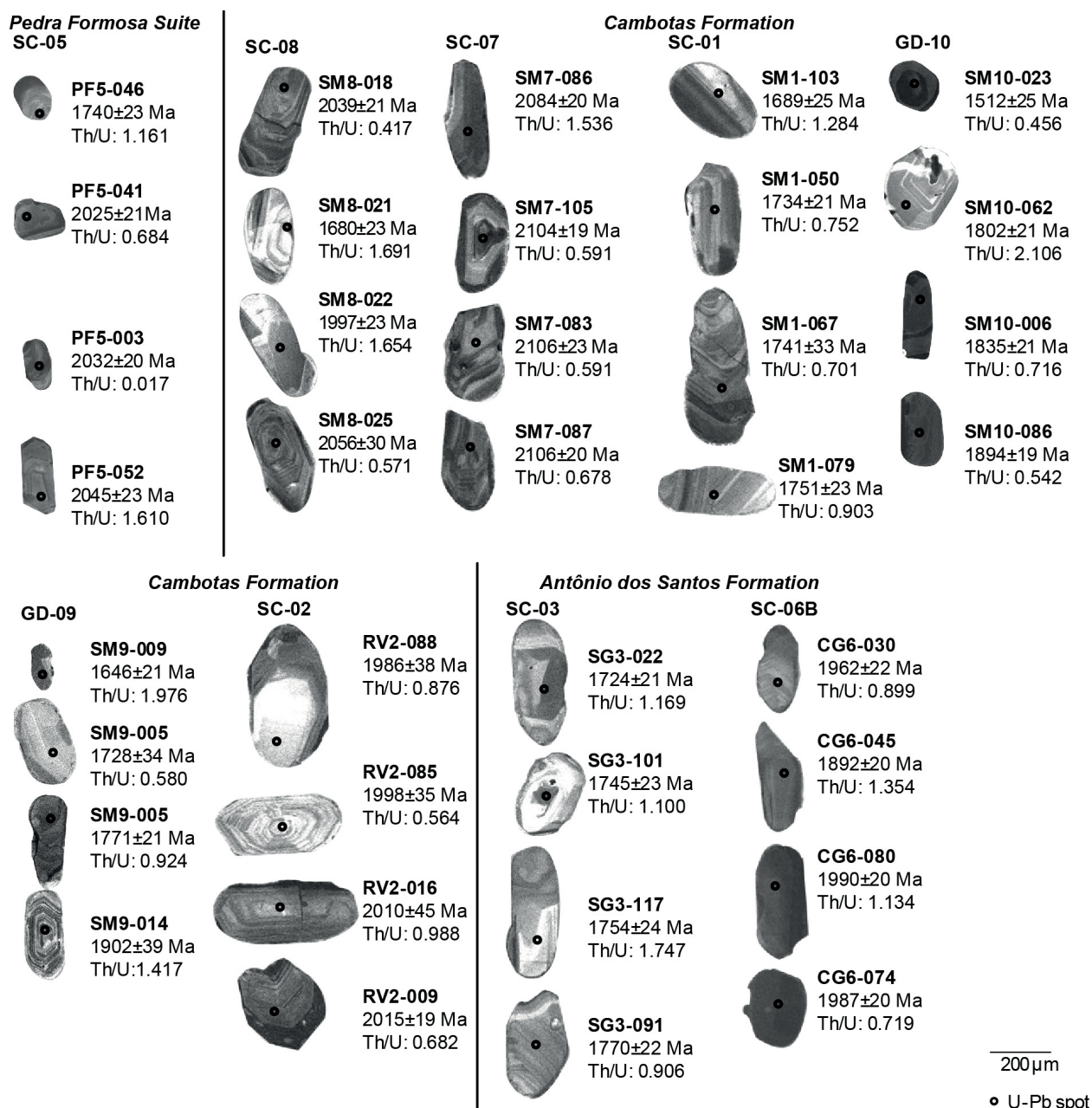


Figure 8. Cathodoluminescence images, $^{207}\text{Pb}/^{206}\text{Pb}$ ages and Th/U ratio of some zircon grains from Tamanduá Group and Pedra Formosa Suite.

Miguel member) record slightly different patterns from the base formation, mostly from Archean age (3109–2523 Ma, n = 11, Rio Vermelho member, Figure 9F), and having its main peak in the Rhyacian-Orosirian period (2300–1802 Ma, n = 221) (Fig. 9). The secondary population of sample SC-02 records ages from 2760 to 2513 Ma (n = 10). The São Miguel member has the youngest and oldest ages of our database, 1512 ± 25 Ma (98.2% conc., sample GD-10, Fig. 9E) and 3268 ± 17 Ma (98.9% conc., sample GD-09, Fig. 9D), respectively.

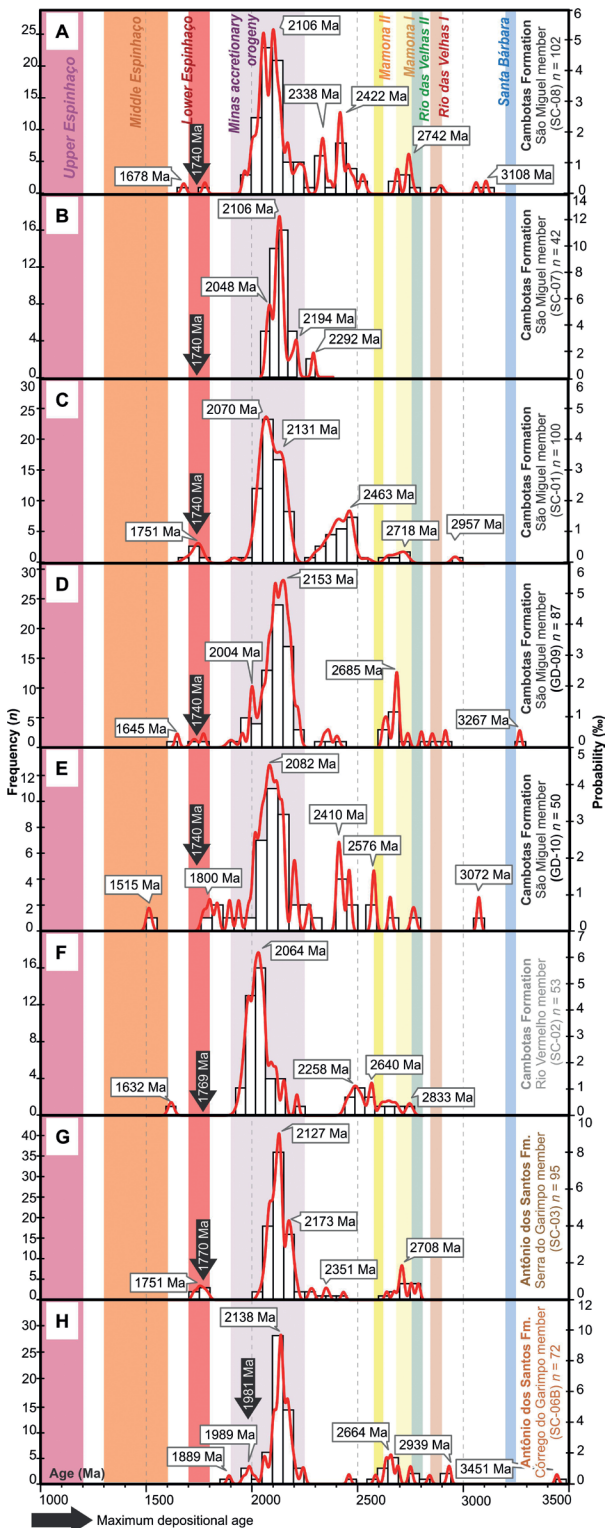


Figure 9. Histogram and maximum depositional age of Tamanduá Group samples.

The zircons of sample SC-05 (Pedra Formosa Suite) are mostly round and CL-dark; few grains are concentric oscillatory- and sector-zoned. Based on zoning patterns and U-(Th)-Pb ages, the zircons are interpreted as inherited zircons (derived grain from melt sources) and zircon xenocrysts (zircon crystals incorporated from surrounding host rocks during the emplacement), as proposed by Miller *et al.* (2007). The youngest concordant zircon was dated at 1740 ± 23 Ma (100.1% conc.) and could indicate the minimum crystallization age of this mafic suite (Fig. 10).

DISCUSSION

Maximum deposition and crystallization age

The maximum deposition age is the most powerful application of detrital zircon geochronology, which contributes useful information for strata that are devoid of volcanic units and fossils (Gehrels 2014). However, some complexities can result in misleading measures as loss of radiogenic Pb, Th/U ratio, and the inadequate number of data. The best way to avoid misleading interpretations is to analyze samples from different levels of a stratigraphic section (Gehrels 2014) and the use of the youngest 2 σ grain cluster (YC2 σ (3+)). This methodology was developed by Dickinson and Gehrels (2009), and it provides that the maximum deposition age of a metasedimentary sample can be measured via weighted mean age or peak age probability of the youngest cluster (n ≥ 3). The youngest single grain (YSG) is compatible in 90% of the studied cases, but it could not pose statistical validity. Table 3 summarizes the application of this methodology on the database.

The age of the youngest grain cluster of each member proved to be more relevant than the individual measure of each sample from detail analyses of the Tamanduá Group maximum deposition age, due to a more significant amount of data that reduce analytical errors (Tab. 4).

In summary, the ages of ca. 1770 and 1740 Ma are assumed as maximum depositional ages from the Antônio dos Santos and Cambotas formations, respectively. The age of the base

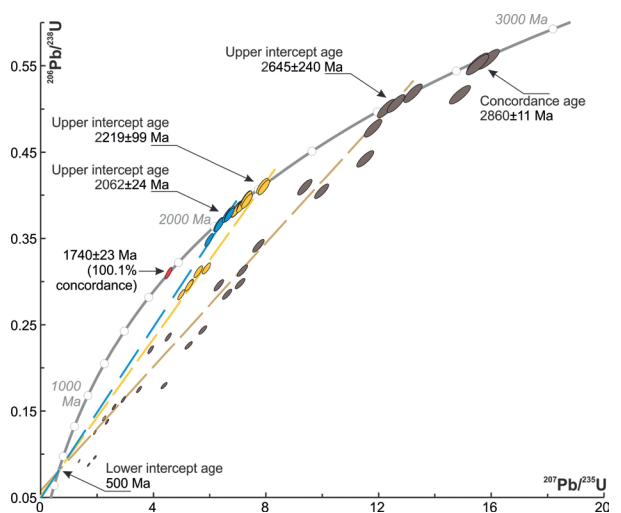


Figure 10. Concordia diagram for Pedra Formosa Suite.

unit of Cambotas Formation, Rio Vermelho member, is measured by the ages of the secondary youngest grains cluster of São Miguel member; otherwise, its age was older than Antônio dos Santos Formation, due to the absence of grain cluster with $n \geq 3$ younger than 1770 Ma. The maximum deposition age of Córrego do Garimpo member was stipulated by the weighted mean age of youngest grain cluster (1981 ± 36 Ma), but the youngest single grain could have geochronological validity considering that it is older than the age of the overlying unit, Serra do Garimpo member (1892 ± 20 Ma, 99.9% conc.).

The single zircon of 1740 ± 23 Ma is interpreted as the minimum age of the Pedra Formosa Suite (Fig. 10), and it is like the magmatic pulse relative to the opening of Espinhaço basin (Silva *et al.* 1995). This data is inaccurate in determining the age of the Pedra Formosa magmatism, although it is compatible with the geological setting of the study area by presenting similar age to that of São Miguel member (1740 ± 12 Ma, Tab. 4), which can be an inherited zircon from this unit. The Th/U rate does not suggest a metamorphic origin to those grains, due to the rate, being more than 0.1.

Provenance and implications for the evolution of the Tamanduá Group

The histograms of detrital zircon ages of metasedimentary rocks of Tamanduá Group (Fig. 9) have age distributions with

main peaks related to the Minas accretionary orogeny ($n = 471$), followed by populations from Meso- to Neoproterozoic periods ($n = 13$, non-specific tectonomagmatic event), Mamona I ($n = 13$) and Santa Bárbara events ($n = 4$). Zircon ages allied with the collisional stage of Minas accretionary orogeny (2250–2080 Ma; Endo and Machado 2002, Aguilar *et al.* 2017) correspond to 67% of its age population ($n = 316$), with the remainder ($n = 155$) being related with the post-collisional magmatism (> 2080 Ma, Aguilar *et al.* 2017). The Rhyacian-Siderian sources were probably plutons of the Mineiro Belt in the southeast of the QF as Alto Maranhão (2130 ± 2 Ma, Noce 1995, 2128 ± 10 Ma, Seixas *et al.* 2013), Ritópolis (2123 ± 33 Ma, Teixeira *et al.* 2014), Rio Grande (2095 ± 12 Ma, Barbosa *et al.* 2015), Serrinha-Tiradentes (from 2227 ± 22 to 2204 ± 11 Ma, Ávila *et al.* 2010, 2014), Lagoa Dourada (2350 ± 4 and 2356 ± 3 Ma, Seixas *et al.* 2012; 2351 ± 48 and 2317 ± 16 Ma, Teixeira *et al.* 2015), Cassiterita (from 2472 ± 11 to 2414 ± 29 Ma, Barbosa 2015), and associated units.

The post-Orosirian ages families ($n = 25$) are the youngest ones and represent two sedimentary cycles (Middle- and Lower Espinhaço) of the Espinhaço System. These zircon ages are related with the intrusive rocks, whose crystallization age ranges from 1724 to 1501 Ma (see Fig. 4 of Guadagnin and Chemale Jr. 2015), as Borrachudos Suite (Dussin and Dussin 1995), K-alkaline (hematite-phyllite) intrusions in the São

Table 3. U-Pb detrital zircon ages of Tamanduá Group in this study.

Unit	Samples	Youngest single grain (concordance)	Youngest grain cluster with $n \geq 3$	
			Peak age probability	Weighted mean age (MSWD)
São Miguel member ^{CF}	SC-08	1680 ± 23 Ma (100.1%)	1967 Ma	1976 ± 42 Ma (2.4)
	SC-07	2030 ± 24 Ma (104.3%)	2048 Ma	2039 ± 9 Ma (0.56)
	SC-01	1689 ± 25 Ma (98.8%)	1751 Ma	1742 ± 13 Ma (0.58)
	GD-09 ¹	1646 ± 21 Ma (101.7%)	2004 Ma	1999 ± 10 Ma (0.03)
	GD-10 ¹	1512 ± 25 Ma (98.2%)	2017 Ma	2028 ± 15 Ma (2.7)
Rio Vermelho member ^{CF}	SC-02	1626 ± 30 Ma (103.9%)	-	1988 ± 22 Ma (0.38)
Serra do Garimpo member ^{AF}	SC-03	1724 ± 21 Ma (100.0%)	1751 Ma	1770 ± 41 Ma (2.0)
Córrego do Garimpo member ^{AF}	SC-06B	1892 ± 20 Ma (99.9%)	1989 Ma	1981 ± 36 Ma (2.0)

¹Samples analyzed by Dutra (2017), ^{CF}Cambotas Formation; ^{AF}Antônio dos Santos Formation.

Table 4. Maximum depositional age of Tamanduá Group units.

Unit	Samples	Youngest single grain (concordance)	Youngest grain cluster with $n \geq 3$		Maximum deposition age
			Peak age probability	Weighted mean age (MSWD)	
São Miguel member ^{CF}	SC-08, SC-07, SC-01, GD-09 ¹ and GD-10 ¹	1512 ± 25 Ma (98.2%)	1744 Ma	1740 ± 12 Ma (0.58)	1740 ± 12 Ma
Rio Vermelho member ^{CF}	SC-02	1626 ± 30 Ma (103.9%)	1776 Ma ²	1769 ± 11 Ma (1.2) ²	1769 ± 11 Ma ²
Serra do Garimpo member ^{AF}	SC-03	1724 ± 21 Ma (100%)	1751 Ma	1770 ± 41 Ma (2.0)	1770 ± 41 Ma
Córrego do Garimpo member ^{AF}	SC-06B	1892 ± 20 Ma (99.9%)	1989 Ma	1981 ± 36 Ma (2.0)	1981 ± 36 Ma

¹Samples analyzed by Dutra (2017); ²age of second youngest grains cluster of São Miguel member samples; ^{CF}Cambotas Formation; ^{AF}Antônio dos Santos Formation.

João da Chapada Formation (Dussin 1994, Chemale Jr. *et al.* 2012), Conceição do Mato Dentro rhyolite (Brito Neves *et al.* 1979, Abreu 1991), and Mato Verde Group (Costa *et al.* 2014, 2018) in the Southern Espinhaço.

The limited contribution of Archean crustal in the Tamanduá basin can be attributed to the continuous process of peneplanation of this terrain and the sediments derived from distant source areas such as Southern Espinhaço.

The Tamanduá basin can be characterized as a long-lived basin in the Statherian period and its stratigraphy evolution is related to two stages of basin filling. The first one is associated with Antônio dos Santos Formation, an early intracontinental rifting sedimentation that was succeeded by a flexural stage, characterized by the rapid deposition (ca. 1.1 km in a maximum period of 30 Myr) of Cambotas Formation (Fig. 11).

The Antônio dos Santos Formation is related to tectonically-driven continental sedimentation under dry conditions. The immaturity of quartz-feldspathic clasts (pebbles and cobbles) of Córrego do Garimpo member's metaconglomerate indicates that the sediments were derived from proximal highlands dominated by granitic-like and supracrustal rocks of QF, indicated by a higher content of banded iron-formation pebbles and cobbles. This sedimentary contribution is recorded by 2500–2000 Ma population in the histogram

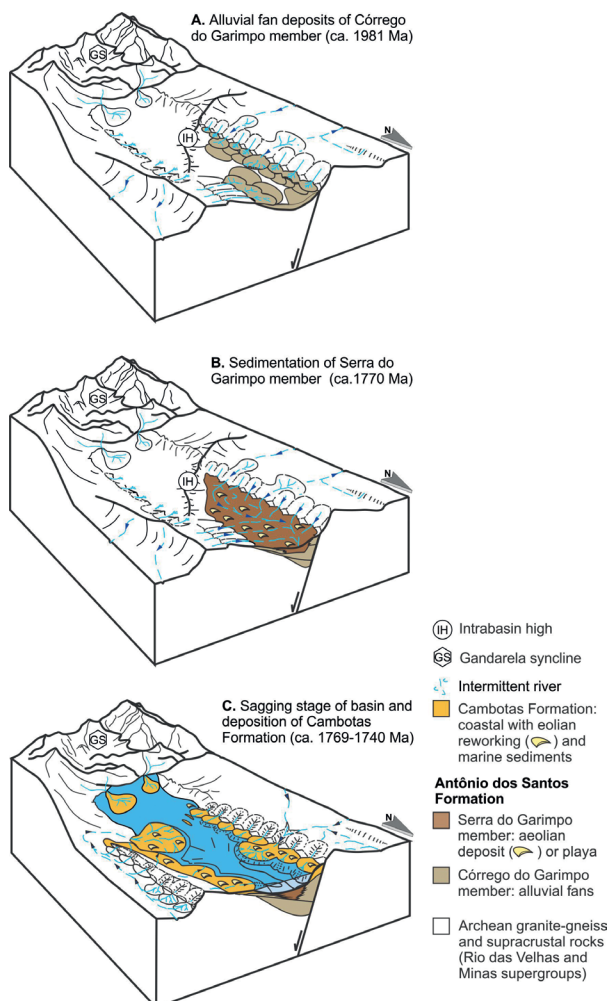
(Fig. 9). The metaconglomerate exhibits a coarsening-upward succession, and the metasandstone in the base of Córrego do Garimpo member shows lens-form with core coarser than borders. Those architectural elements indicate this sedimentation was in an aluvial fan environment, located near the rift border fault. It can be inferred because of the significant deformation of the metaconglomerate next to the contact with the granite-gneiss complex, which indicates adjacent highlands to deposits during the basin inversion process. The abundance of granitic pebbles and cobbles suggests a tectonically active setting in an arid to semi-arid climate, where the well-rounded grains of quartz support eolian abrasion of loose detritus on stable landforms (Patranabis-Deb and Kumar Chaudhuri 2007). The permanence of arid to semi-arid climate propitiated the aeolian deposition of Serra do Garimpo member at ca. 1770 ± 41 Ma, and despite its restricted occurrence, this member could record the tectonic quiescence of the Tamanduá basin (Fig. 11). The geochronological data of Antônio dos Santos Formation possibly indicates a paraconformity between the Serra do Garimpo and Córrego do Garimpo members which probably corresponds to a hiatus of ca. 240 Myr. The controlled expression of the Antônio dos Santos Formation may suggest a segmentation of the basin due to transfer fault. This structure is oblique to the rift border fault and uplifts as intrabasin high (IH) (Figs. 11A and 11B).

The increase of basin subsidence led to marine incursion and changes in depositional style and source areas. We interpret the variations in Mesoproterozoic age from the base to the upper part of the Tamanduá Group as a rejuvenation effect of the base and middle portions of the Cambotas Formation (samples GD-10 and SC-08, respectively). The sagging stage of Tamanduá basin, represented by the Cambotas Formation, unconformably overlies the Antônio dos Santos Formation.

The nature of the erosional contact between the top unit of Antônio dos Santos Formation (Serra do Garimpo member) and the basal one of Cambotas Formation (Rio Vermelho member) is abrupt, due to its very similar maximum depositional ages and the change of depositional style followed by a concomitant change of sources. The Rio Vermelho member records the coastal deposits marked by a significant contribution of Orosirian-Statherian source areas (Fig. 9), whose feldspar grain preservation indicates the permanence of arid to semi-arid climate. The São Miguel member registers the transition of coastal to marine sediments; this sedimentation could be influenced by eolian contributions as suggested by grain size predominance and sedimentary stratifications. The upper unit, Ribeirão Cocais member, points to the rise of sea level over clastic rocks of base units of Tamanduá basin (Fig. 11).

Our stratigraphic framework and the U-Pb age patterns ally the Tamanduá Group to the Mesoproterozoic Espinhaço rift-sag system (Chemale Jr. *et al.* 2012, Guadagnin and Chemale Jr. 2015).

Based on our geochronological data, the maximum depositional age of Serra do Garimpo member (Antônio dos Santos Formation, 1770 ± 41 Ma) suggests a chrono-correlation with the early sedimentation units of Statherian rifts (Fig. 12). The maximum deposition age of Serra do Garimpo member indicates



Source: based on Figures from Gawthorpe and Leeder (2000).

Figure 11. Tectono-sedimentary evolution of Tamanduá Group.

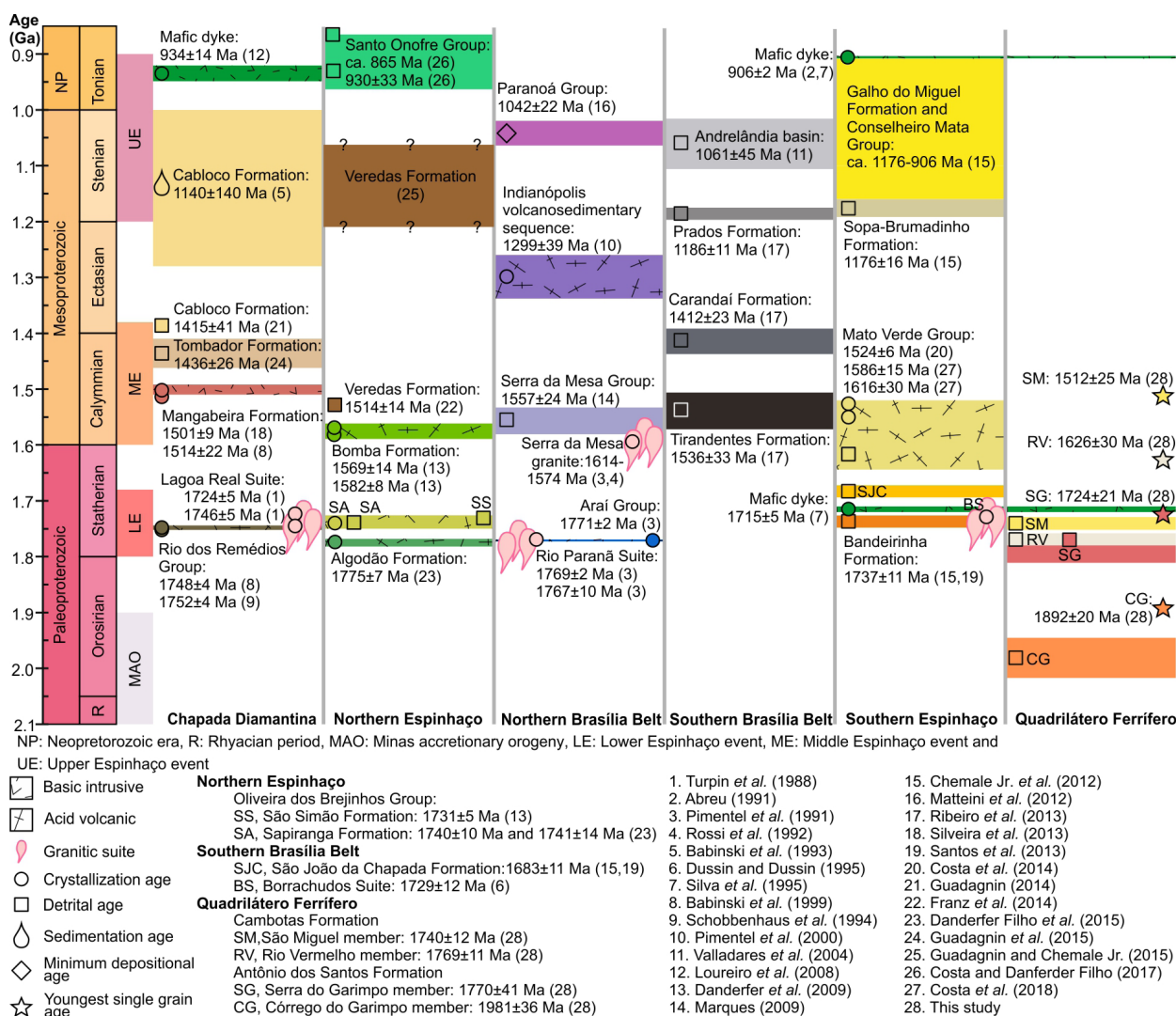
equivalence with the Statherian rhyolite (1771 ± 2 Ma) associated with initial syn-rift sedimentation (alluvial fan, braided river, eolian, and lacustrine deposits; Alvarenga *et al.* 2000) of the Araí Group (Pimentel *et al.* 1991) and the granitic plutons of Rio Parana Suite, which shows crystallization age of Soledade and Sucuri granite of 1769 ± 2 and 1767 ± 10 Ma (Pimentel *et al.* 1991), respectively. Furthermore, the volcano-sedimentary successions of Algodao rifting (Northern Espinhao) record similar ages, 1775 ± 7 Ma (Danderfer Filho *et al.* 2015).

The maximum depositional ages proposed from Sao Miguel member (Cambotas Formation) indicates a correlation with Bandeirinha Formation in the Southern Espinhao, Rio dos Remedios Group in the Chapada Diamantina, and Sapiranga Synthem in the Northern Espinhao. The Bandeirinha Formation represents the alluvial fan conglomerates, braided river, and eolian deposits from the rift basin deposited in 1737 ± 11 Ma (Chemale Jr. *et al.* 2012, Santos *et al.* 2013). The Rio dos Remedios Group encompasses acid lavas and lacustrine to alluvial sediments, this magmatism is dated 1752 ± 4 (Schobbenhaus *et al.* 1994) and 1748 ± 4 Ma (Babinski *et al.* 1999), and it is coeval with Lagoa Real granitic-gneiss complex, whose emplacement ages range from 1750–1710 Ma

(Turpin *et al.* 1988, Lobato *et al.* 2015). The Sapiranga Synthem is characterized by a conglomerate with voluminous clasts of volcanic rocks, sandstone, and crystalline rocks and showed age of 1740 ± 11 Ma (Danderfer *et al.* 2009).

If considering just the youngest zircon grains, the Tamandua Group sedimentation could range from Lower (1.80–1.68 Ga) to Middle Espinhao (1.60–1.38 Ga) events (Fig. 12). The Antonio dos Santos Formation (1724 ± 21 Ma, 100.0% conc.) would be chrono-correlated with continental sediments of the Lower Espinhao event, while the sedimentation of Cambotas Formation would be focused solely in the Middle Espinhao event at 1512 ± 25 Ma (98.2% conc.) and chrono-correlated with the Veredas (Northern Espinhao, maximum depositional age at ca. 1500 Ma; Franz *et al.* 2014) and Tiradentes Formations (Southern Brasilia Belt, 1514 ± 14 Ma, Ribeiro *et al.* 2013).

The stratigraphic stacking of the Tamandua Group seems to be correlated to Stenian-Tonian units of the Southern Espinhao Supergroup. However, there are no key units to make it clear. As proposed by Gomes (2017), the Antonio dos Santos Formation show lithological similarities with Galho do Miguel and Sopa-Brumadinho formations, whereas the Cambotas Formation with the Conselheiro Mata Group.



Source: based on Figures from Guadagnin and Chemale Jr. (2015).

Figure 12. Temporal relations of lithostratigraphic units of the Espinhao system.

In this scenario, the Antônio dos Santos Formation would represent a local segment of the Stenian rift systems that took place in the eastern border of SFC, limited to the north by the Caeté Complex, and to the south by the Gandarela syncline, both acting at the same time as structural highs and local sediment sources.

The Cambotas Formation would correspond to a short section of the marine deposits of the Conselheiro Mata Group, recording an intracratonic sag basin as described by Lopes (2012) and Santos *et al.* (2015). The provenance is related to the recycling of ancient sources, typical of a craton interior sag basin, and, secondarily, the input of younger sources, most likely from the underlying rift basin (Santos *et al.* 2015).

We emphasize that the maximum depositional ages proposed here do not exclude this possible chrono-correlation, but the geochronological database does not statistically support it.

CONCLUSIONS

Based on our field and U-Pb data, the following conclusions are emphasized:

- The Tamanduá basin can be characterized as a long-lived basin related to two stages of basin filling. The first one is associated with Antônio dos Santos Formation, an early intracontinental rifting sedimentation succeeded by a flexural stage, characterized by the rapid deposition of the Cambotas Formation;
- The Antônio dos Santos Formation is related to tectonically-driven continental sedimentation under dry conditions. The Córrego do Garimpo Member, on the bottom, indicates that the sedimentation was in an alluvial fan environment close to rift border faults, composed by granitic-like rocks and supracrustal rocks of QF. The permanence of arid to semi-arid climate propitiated the eolian deposition of Serra do Garimpo member on top, recording the tectonic quiescence of Tamanduá basin and its segmentation due to transfer faults oblique to NS rift axis;
- The geochronological data of Antônio dos Santos Formation is dominated by Rhyacian-Siderian sources, corroborating the hypothesis of QF acting as a structural high, at the

south, during its deposition. The data also indicate a possible paraconformity between the Serra do Garimpo and Córrego do Garimpo members (ca. 240 Myr);

- The U-Pb detrital zircon pattern of the Tamanduá Group presents sources from the Paleoproterozoic to the Calymmian period. The proposed maximum age deposition for the Tamanduá Group is ca. 1740 Ma;
- The sag stage of Tamanduá basin is represented by the Cambotas Formation, overlying by unconformity the Antônio dos Santos Formation. The Rio Vermelho member records the initial subsidence of the basin and the beginning of the marine incursion. In contrast, São Miguel and Ribeirão Cocais members point to the rise of sea level over Antônio dos Santos Formation. The deposition of this formation records the recycling of older sources due to uplift, exposure, weathering, erosion and sedimentary transport of Paleo- to Mesoproterozoic terranes;
- The Pedra Formosa Suite crosscuts the metasedimentary package of the Tamanduá Group and has to be younger than 1740 Ma;
- We reinforce in this work the stratigraphic positioning of the Tamanduá Group as part of the Paleo-Mesoproterozoic Espinhaço rift-sag system. Our data exclude it from the Paleo-Neoproterozoic Rio das Velhas and Neoproterozoic-Siderian Minas supergroups of the QF.

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